An Overview of Diesel Particulate Exposures and Control Technology in the U. S. Mining Industry

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Abstract

Studies of diesel particulate exposures in the U.S. mining industry indicate that diesel particulate exposures in surface mining operations are generally less than 200 $\mu g/m^3$. Average diesel particulate exposures in underground coal mines using diesel-powered equipment ranged from 100 to 2,100 $\mu g/m^3$. Average diesel particulate exposures in underground metal and nonmetal mines ranged from 300 to 1,600 $\mu g/m^3$.

The purpose of this paper is to provide an overview on worker exposure to diesel particulate matter (DPM) and to discuss the effect of control technology on that exposure. Worker exposure has been assessed from in-mine diesel particulate measurements. The effect of control technology has been evaluated by a systems approach which includes: engine emission rate, mine ventilation system and the effectiveness of engine after treatment devices.

Studies conducted by the Mine Safety and Health Administration (MSHA) and the Bureau of Mines (BuMines) show that the primary mmethods, currently employed by the mining industry, to control workers exposure to DPM include mine design, ventilation, engine maintenance and the use of low sulfur fuel. Additional reductions in exposure can be obtained through the use of electronic engine technology. Commercially available after-treatment devices are capable of reducing DPM by 25 to 95 percent. Reductions in exposure to DPM are dependent on the application of available engine emission control technology and modifications to mine ventilation systems.

Introduction

Diesel-powered equipment is utilized in most aspects of surface coal mines, surface metal and nonmetal (M/NM) mines, underground M/NM mines and in some underground coal mines. Since the 1970's, the use of diesel-powered equipment in underground coal mines has increased. Many types of mobile diesel-powered equipment are operated in the mining industry.

Several organizations have indicated that there is a concern about the potential carcinogenicity of diesel particulate. That concern extends into mining operations because of the exposure levels. Diesel equipment is used in approximately 13,500 mining operations in the United States. These operations include approximately 300 underground and 11,000 surface metal and nonmetal mines and 180 underground and 2,000 surface coal mines. MSHA estimates that approximately 230,000 miners are working at these mines.

Exposure to diesel particulate in mines is related to three primary factors (Holtz, 1960; Waytulonis, 1992). These factors include: engine emissions levels, exhaust aftertreatment efficiency and in underground mines, ventilation rate. Because of th e interrelation of the various control technologies to worker exposure, mine operators have the option to choose the combination of controls that best suit their operations. In some cases, because of the number and size of equipment, ventilation alone may be sufficient to control worker exposures. In other cases, it may be necessary to reduce engine emissions and/or utilize after treatment devices.

Currently there are no specific regulations for controlling diesel particulate (Anon., 1994). The current regulations pertain to ambient gaseous pollutant levels and limits the gaseous contaminants of diesel exhaust. MSHA regulates emissions from diesel equipment in metal and nonmetal mines through the air quality requirements of 30 CFR, Parts 56/57.5001. These regulations limit the concentrations of airborne contaminants to the 1973 Threshold Limit Values (TLV's). Under Part 57.8520, operators of underground metal and nonmetal mines develop a ventilation plan that includes a characterization of diesel equipment.

MSHA regulates emissions from diesel-powered equipment used in coal mines through the air quality requirements of 30 CFR, Parts 71.700 and 75.322; through ventilation requirements of 75.325 and 75.371; and through clean engine requirements of 30 CFR Parts 7, 36 and 75.1907. These regulations limit the concentrations of noxious or poisonous gases to the 1972 Threshold Limit Values (TLV's). Under Part 75.371, operators of underground coal mines must develop a ventilation plan which would include mine-specific controls used to control diesel emissions.

The purpose of this paper is to provide an overview on worker exposure to diesel particulate matter (DPM) and to discuss the effect of control technology on that exposure. Worker exposure has been assessed from in-mine diesel particulate measurements. The effect of control technology has been evaluated by a systems approach which includes the influence of engine emission rate, mine ventilation and the effectiveness of engine aftertreatment devices.

Mining Exposures and Measurement Methods

Several methods have been developed to measure airborne dust samples for diesel particulate matter. These methods include the use of size selective devices (Staff, BuMines, 1992); the measurement of respirable combustible dust (RCD) (Haney, 1992); and the measurement of elemental carbon (Birch, 1992). The size selective and RCD methods provide measurements of whole diesel particulate. The elemental carbon method provides a surrogate measurement of diesel particulate. The size selective and RCD methods are limited by gravimetric analysis. RCD can only be used in noncoal mines. The elemental carbon method is limited by filter loading. Both the MSHA and the BuMines have continued to maintain active programs for characterizing DPM exposure levels in coal and metal and nonmetal mining operations that utilize diesel-powered equipment.

Studies conducted by the MSHA of diesel particulate exposures in the U.S. mining industry indicate that diesel particulate exposures in surface mining operations are generally less than 200 $\mu g/m^3$. The higher exposures are typically associated with front-end loader operators and haulage-truck operators. Exposure appears to be more related to the specific operating conditions than the size of the engine.

The average and range of all occupational exposure measurements of face workers obtained from MSHA studies conducted in coal mines since January of 1991 have been summarized in Figure 1 (Tomb, 1995). In most of the mines, measurements were obtained with and without a diesel exhaust aftertreatment device being used. The aftertreatment device used by all but one of these mines was a disposable diesel exhaust filter (DDEF). The other mine was using a wire mesh filter that could be reused after cleaning.

The average DPM concentration for occupational exposures, when exhaust after treatment devices were not used, ranged from 700 to 2,100 $\mu g/m^3$. Average occupational exposures ranged from 100 to 200 $\mu g/m^3$ when using the DDEF and was 1,200 $\mu g/m^3$ when using the wire mesh filter. For operations using the DDEF, occupational exposures were found to be reduced by approximately 95 percent. For the operation using the wire mesh reusable filter, occupational exposures were reduced by approximately 50 percent. The higher concentrations at the mine using the wire mesh filter were partly attributed to the lower section airflow. The section airflow at the mine using the wire mesh filter was 7.5 m^3/s. The section airflowsat the mines using DDEF ranged from 15 to 30 m^3/s.

The average and range of occupational exposures obtained for face workers in the MSHA studies of metal and nonmetal mining operations are summarized in Figure 2. None of the metal and nonmetal mines studied were using exhaust aftertreatment devices. Average occupational exposures ranged from approximately 350 to 1600 μg/m^3. Overall, occupational exposures averaged approximately 700 μg/m^3.

In addition to measuring occupational exposures, the rate that DPM was generated in the respective mines was estimated. The particulate generation rates were calculated using return air ventilation quantities and the concentration of DPM in the intake and return airways. As shown in Figure 3, for coal mine operations not using exhaust aftertreatment devices, the generation rates varied from 1.2 to 1.8 g/min. These generation rates shown have not been normalized for the number or horsepower of vehicles operating. The primary sources of DPM emissions were from two to three diesel haulage vehicles. Results of the MSHA studies indicated that the rate DPM was generated was reduced by as much as 95 percent when vehicles were equipped with the disposable filters.

The DPM generation rates were also estimated for the metal and nonmetal mines studied. The generation rates from the MSHA studies are shown in Figure 4. They ranged from 0.9 to 10.3 g/min. Even with the higher generation rates, occupational exposures were half of those found in coal mines. This was due to the large quantities of air (18 to 117 m^3/s) used to ventilate the working areas. Metal and nonmetal mine diesel particulate generation rates were also not normalized for number and horsepower of equipment in operation.

Ventilation

Mine ventilation has been the primary means of controlling diesel emissions in underground mines. A mine ventilation system must be designed to provide and distribute sufficient airflow to areas of a mine where diesel equipment is being used. Diesel particulate is small in size and behaves similar to a gas once it becomes airborne. Ventilation dilutes the particulate emission after it has been released into the environment. As airflow increases, diesel particulate concentration decreases.

Coal Mines: The ventilation system for an underground coal mine is generally well defined. Air is coursed through a series of entries from the surface to the active faces. Intake entries are separated from return entries by a series of stoppings and overcasts. Stoppings are maintained to and including the third connecting crosscut from the face. Each working section is ventilated on a separate air split. A regulator is used to adjust and control the airflow on the air split. Statutory minimum air flow must be maintained in the last open crosscut and at the working face. Higher airflows may be required in the mine ventilation plan.

When a single piece of diesel equipment is operated in coal mines, the nameplate airflow must be provided as minimum airflow requirements. When multiple pieces of diesel equipment are operated, the minimum section airflow is the sum of the nameplate airflows for the individual pieces of equipment. This requirement was developed to control the gaseous diesel emissions. Transportation and supply vehicles are generally excluded from this calculation. Specific mine-by-mine requirements are stated in the approved Ventilation Plan.

Underground M/NM Mines: When diesel equipment has been used in metal and nonmetal mines, a guideline of 75 to 200 cfm/hp has been used to establish airflow requirements. This guideline is generally met, based on the amount of equipment operating and total mine airflow. However, based on the total equipment present in an underground mine, this guideline may not be met. Adequacy of airflow has been judged by gaseous air quality measurements. With the gaseous air quality requirements being met, the diesel particulate exposures have ranged from 500 to 1,000 $\mu g/m^3$.

Metal and nonmetal mines can be ventilated in a variety of ways. In single level mines, working areas are generally ventilated in series. The exhaust of one area becomes the intake for the next area. Multi-level mines may provide a separate air split to each level or to several levels. Because of the opening sizes, it is difficult to maintain separation between intake and exhaust air courses. As a result, leakage or loss of fresh air can be extreme. Localized airflow distribution is provided by auxiliary and booster fans installed through out the mine.

Exhaust Dispersion Methods and Devices

Proper dispersion of diesel exhaust emissions into the surrounding mine atmosphere can reduce exposures by minimizing occurrences of undiluted pollutants. Dispersion is not an emission control because it does not remove exhaust pollutants. It does, however, provide for a more effective use of the mine airflow to dilute diesel pollutants.

An effective and common means of dispersing diesel exhaust into the ventilation system is to release the exhaust gas into the moving air from the radiator fan. This reduces the danger from local areas becoming contaminated and from the engine rebreathing exhaust gases. For liquid-cooled engines (with pusher fans), the exhaust flow can be directed into the airstream in front of the radiator.

Jet-type exhaust dispersion devices, i.e. fume diluters, entrain surrounding air and direct the diluted exhaust away from the machine operators position. The exhaust gas is piped into the fume diluter manifold and released through a pre-set annular gap before it passes over an aerofoil surface. The high velocity of the jet creates an area of low pressure that inducts the surrounding air into the throat of the fume diluter. The disadvantage of fume diluters is that they increase back pressure on the engine. Particularly appropriate applications are on diesel machines operated in tunnel development or dead-end headings.

Control of Engine Emissions

Engine emission rates are an important factor in diesel particulate exposures. As the amount of pollutants produced by an engine increases, particulate exposures also increase. Engine emissions are governed by engine design, fuel quality, work practices and maintenance practices. Reducing engine emissions reduces the amount of particulate that would have to be controlled by other means.

Engine Design: In order to meet the stringent emission requirements for on-highway trucks, engine manufacturers are developing methods to reduce engine diesel particulate emissions. Improved technology in combustion chamber design and fuel pump injection system have contributed to lower DPM emissions. Other changes that are occurring include: the increase in the number of intake valves, changes to piston design, ring design, higher fuel injection pressures, minisac injection nozzles, after cooler utilization turbo charging and electronic controls. While initially developed for large on-highway engines, this technology is being transferred to the smaller horsepower engines. As the smaller engines become more regulated worldwide, the transfer of clean engine technology to the mining industry will increase. These improvements to engine design can reportedly reduce diesel particulate emissions by as much as 90 percent.

Fuel Quality: The sulfur content of the fuel is an important parameter that relates to diesel particulate emissions. In October, 1993, the United States Environmental Protection Agency enacted regulations requiring the use of low sulfur (less than 0.05 percent sulfur) diesel fuel for over the highway vehicles. While this rule does not require the use of low sulfur fuel for off-highway or underground mining operations, it does make low sulfur fuel available nationwide.

The use of low sulfur fuel provides several benefits to the mining industry. It reduces engine particulate emissions up to 30 percent. It reduces some of the objectional odors associated with diesel use and it permits the use of oxidation catalytic converters on nonpermissible equipment. A further benefit in the use of low sulfur fuel is reduced engine wear and reduced maintenance costs. The use of catalytic converters also provides some reductions in hydrocarbons and carbon monoxide.

Work Practices: Fleet management can play an important role in reducing diesel particulate emissions. Older type vehicles should be removed from service or placed in limited service. Operators can optimize equipment use by replacing multiple older vehicles in poor condition with a newer type multipurpose machine. Engine and transmission should be sized to perform the work needed based on the mine conditions. Engine lugging or operating the engine at high load-low speed will significantly increase DPM and gaseous emissions, and increase operating temperature. The mine operator can train the machine operators to shift gears to run the engine at a higher speed to perform the same amount of work and emit less exhaust pollution.

Maintenance: A diesel engine maintenance program can keep engines in optimum operating condition and extend useful engine life. Preventive maintenance, periodic repairs, and adjustments are all part of a basic maintenance program. Lack of maintenance can have a significant effect on the specific emission levels for DPM and gases. The fuel rate must be adjusted for engines operating at higher altitudes. The maximum fuel rate must be decreased as air density decrease, to maintain the proper fuel: air ratio.

Exhaust Aftertreatment

When ventilation and emission reductions do not result in the reduction of diesel particulate levels to the desired concentrations, some type of aftertreatment devices must be utilized. Aftertreatment devices capture and/or transform particulate and gaseous pollutants prior to being released into the environment. Aftertreatment devices include oxidation catalytic converters, disposable paper filters, and reusable ceramic filters.

Oxidation Catalytic Converters: A catalyst is a substance that alters the rate of a chemical reaction without being consumed. In diesel exhaust, gas-phase reactions normally proceed at a very slow rate. With the catalyst, however, the rate is fast enough to be of practical value for controlling emissions. Catalytic converters consist of a metal or ceramic substrate coated with the catalyst and housed in a stainless steel canister. Noble metals (platinum and palladium) are typically used as the active components of the catalyst. The function of catalytic converters is to oxidize exhaust pollutants. As hot exhaust gas passes over the catalyst, CO and HC (including aldehydes) are oxidized to CO_2 and water vapor, reducing the amount of CO, HC, and offensive odors in the exhaust. Catalysts are also effective in reducing the soluble organic fraction portion of DPM. Oxidation catalytic converters can reduce diesel particulate emissions by 10 to 50 percent.

The converter should be located as close as possible to the exhaust manifold to ensure maximum exhaust gas temperature. The catalyst formulation and its operating temperature are critical factors in converter performance. The temperatures required for 50 percent conversion of CO and HC are typically about 370°F (188 °C) and 500°F (260 °C), respectively. As higher exhaust-gas temperatures are attained, conversion efficiency increases. The use of high sulfur fuel reduces the life of catalytic converters.

<u>Diesel Particulate Filters</u>: A number of filter materials are currently being used in diesel particulate after treatment devices. These materials include: ceramic monoliths (cordierite), ceramic yarns, paper, and synthetic fiber materials. Particulate control systems utilizing these materials typically have removal efficiencies ranging between 60 and 95 percent. The two most commonly used aftertreatment filter devices are disposable paper filters and ceramic filters.

Disposable Diesel Exhaust Filters can be used with a water scrubber or a dry heat exchanger system. Exhaust temperature control is required to control the fire hazard. The filter system consists of a filter element, filter housing, and exhaust back pressure indicator. This paper fiber filter element is similar to intake air filters used on large on-highway diesel trucks and can safely sustain up to about 212°F (100 °C) operating temperatures. The filter elements presently in use have a service life of about one to three shifts, after which they are discarded.

Disposable/Reusable Diesel Exhaust Filters are used on engines with exhaust temperatures below about 392°F (200 °C) or less and consist of a low-restriction muffler, back pressure indicator, over-pressure relief valve, over-temperature bypass valve, filter housing, and filter element. This system uses a synthetic filter material and was originally developed for diesel-powered forklifts. The filter elements can be cleaned and reused several times before disposal, due to deterioration, becomes necessary.

Ceramic Particulate Filters can be either wall flow filters or a woven fiber filter. In the wall flow filter, the ceramic material is extruded to form porous channels running the length of the substrate with alternate, adjacent channels blocked off at opposite ends. Exhaust enters open channels at the front of the substrate and is forced through the porous walls where it is filtered. Also, the substrate can be coated with a catalytic material that effectively reduces the temperature necessary for regeneration.

The woven fiber filter systems utilizes high temperature-tolerant ceramic yarn as a filter medium and an electric heater for regeneration. Cartridges are made from a wound fiber that allows them to flex and therefore be tolerant to breakage from thermal cycling and vibration. Individual filter cartridges can be combined to suit different engine sizes, since each filter has its own heating element. Woven fiber filters can be electrically regenerated via on-board or off-board power.

Ceramic wall flow filters can be regenerated either on board or off board in an oven. On board regeneration requires a specific duty cycle that maintains the exhaust temperature at least 842^{o}F (450 ^{o}C) for an interval of at least 15 minutes. The wall flow filter regeneration (ignition) temperature can be lowered to about 750^{o}F (399 ^{o}C) by coating the substrate with noble metal catalysts and to 830^{o}F (443 ^{o}C) by coating with base metal catalysts.

Interrelationship of Controls

Each of the three factors, mine ventilation, engine diesel particulate emissions, and the effectiveness of engine after-treatment devices, impacts diesel particulate exposure. The mine ventilation system provides air quantity and air flow distribution where diesel equipment is operated. Diesel exposure is inversely proportional to the ventilation rate. As ventilation increases, the diesel exposure decreases and as ventilation decreases, the diesel exposure increases (Haney, 1992).

Engine emissions are governed by engine design, fuel quality and maintenance. Exposure is directly proportional to engine emissions. As the emissions go up or down, the resulting exposure correspondingly goes up or down. Engine emissions can range from 0.3 to 0.5 g/min for a diesel haulage vehicle to 1.0 to 3.0 g/min for a large truck or loader (Tomb, 1995).

Diesel exhaust aftertreatment can include oxidation and/or filtration devices. Aftertreatment efficiencies can range from 50 to 95 percent. It is important to note that an after-treatment device that is 90 percent efficient is twice as effective for removing diesel particulate as an 80 percent efficient device. That is because 10 percent instead of 20 percent of the particulate would be remain in the environment.

The concentration of airborne diesel particulate can be estimated from the formula:

$$\text{Concentration} = \frac{\text{Emission} \times (1 - \text{Control Eff.}) \times 1000 \times 35{,}317}{\text{Ventilation Rate}}$$

Where:

Concentration is in $\mu g/m^3$,
Emissions are expressed in grams per minute, g/min,
Control Efficiency is expressed as a decimal,
Ventilation Rate is in cubic feet per minute, cfm.

The graph in Figure 5 was developed using this relationship. The graph shows the interrelationship among exposure, emissions, aftertreatment and ventilation. For a given emission rate, ventilation and aftertreatment efficiency can be determined to control emissions to the required exposure.

As calculated from the above equation, the exposure for a 1 g/min diesel particulate generation rate (with no after treatment) and an airflow of 30,000 cfm would be 1180 $\mu g/m^3$. Doubling the airflow to 60,000 cfm would reduce the exposure by one-half to 590 $\mu g/m^3$. Applying an 80 percent aftertreatment system would reduce the exposure by 80 percent to 120 $\mu g/m^3$ [590 x (1-0.8)].

Summary

Ventilation has been the primary means of controlling diesel emissions in underground mines. Ventilation dilutes the particulate emission after it has been released into the environment. Typical ventilation rates in metal and nonmetal mines range from 75 to 200 cfm/hp. In coal mines, the nameplate ventilation rates are typically used to determine the plan airflow requirement.

Recently there has been a great deal of effort in the mining industry to reduce diesel pollutant exposures by reducing engine emissions and/or through the use of aftertreatment devices. Engine emissions are governed by: engine design, fuel quality, work practices and maintenance practices. Reducing engine emissions reduces the amount of particulate that needs to be controlled by other means. Aftertreatment devices include oxidation catalytic converters, disposable paper filters, and reusable ceramic filters. Aftertreatment devices capture and/or remove particulate prior to being released into the environment.

Because of the interrelation of the various control technologies to worker exposure, mine operators have the option to choose the combination of controls that best suit their operations. In some cases, because of the number and size of equipment, ventilation alone may be sufficient to control worker exposures. In other cases, it may be necessary to reduce engine emissions and/or utilize aftertreatment devices.

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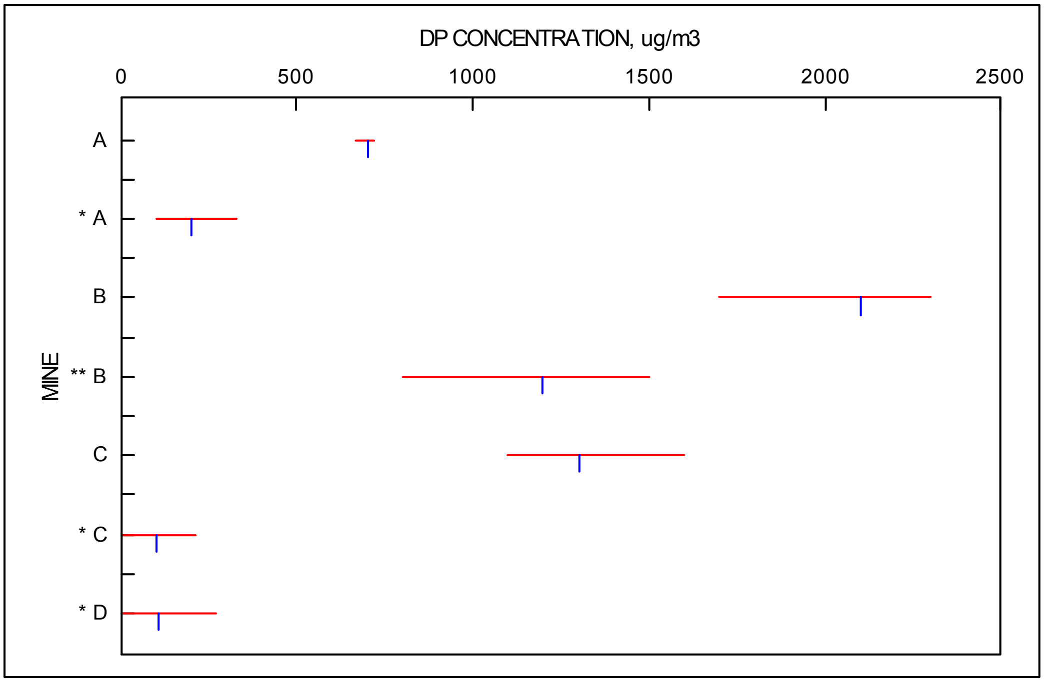

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Figure 1. Summary of Diesel Particulate Levels in Underground Coal Mines.

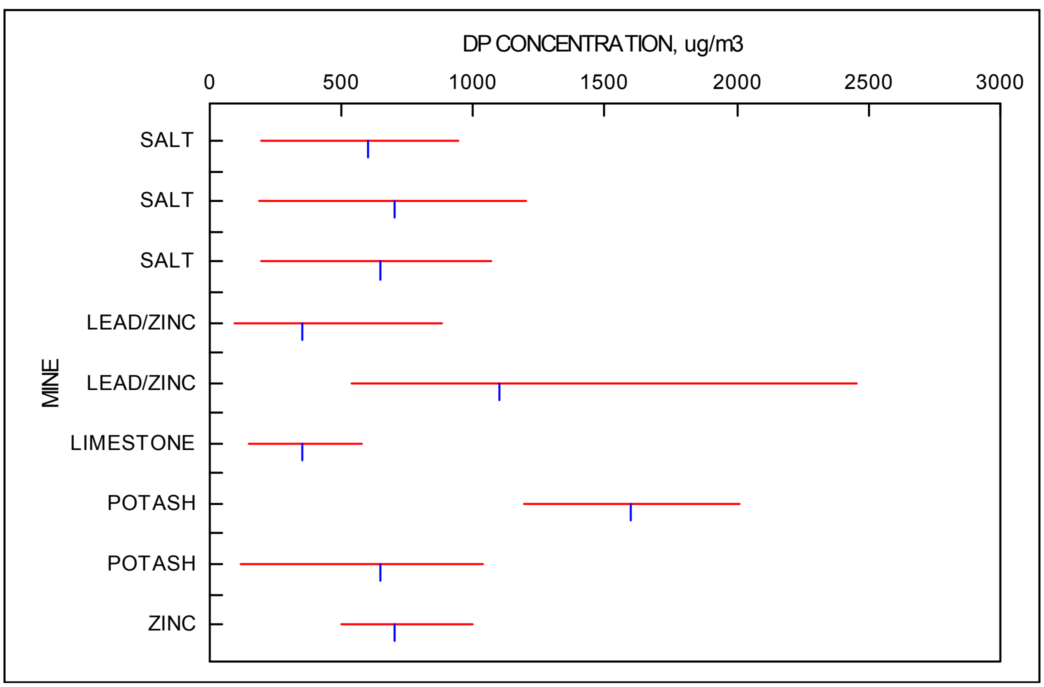

Figure 2. Summary of Diesel Particulate Levels in Underground Metal and Nonmetal Mines.

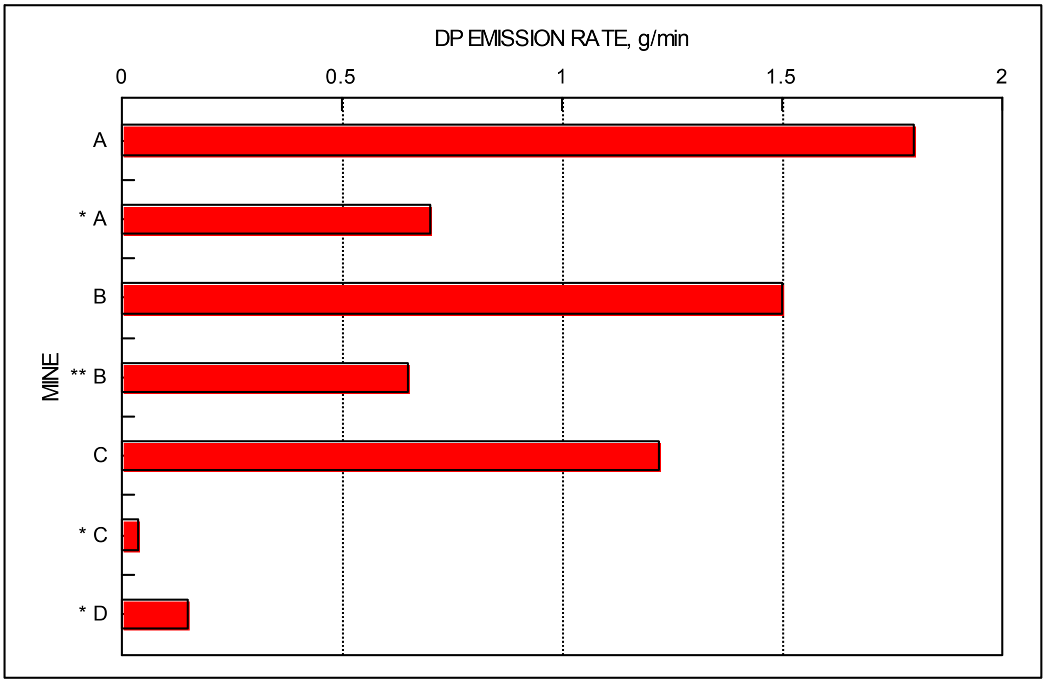

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Figure 3. Summary of Diesel Particulate Emission Rates in Underground Coal mines

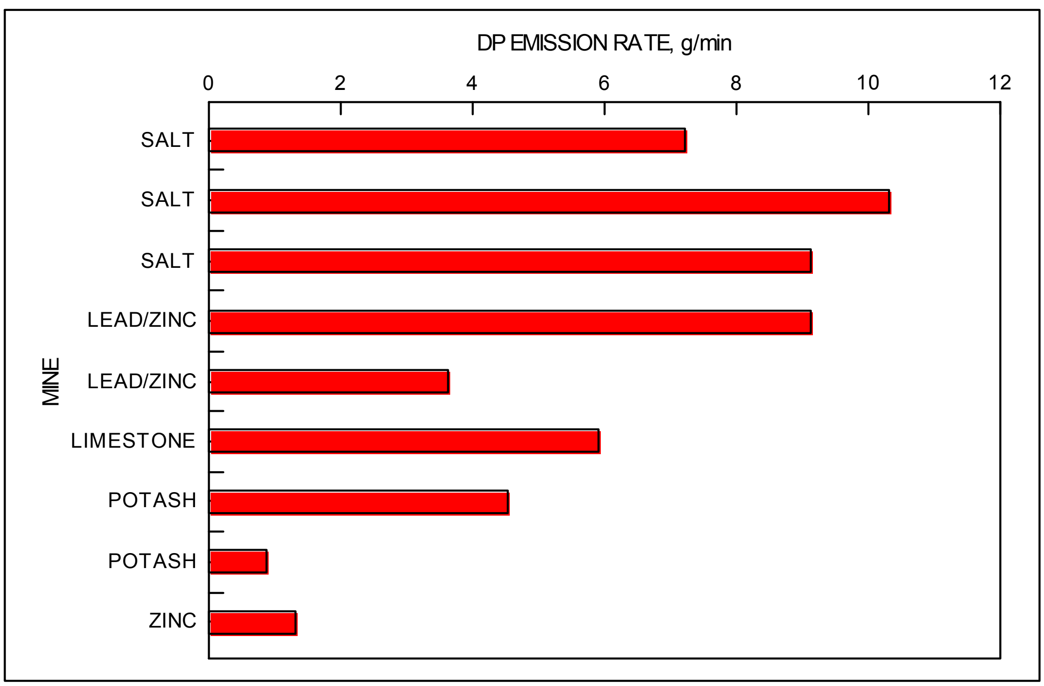

Figure 4. Summary of Diesel Particulate Emission Rates in Underground Metal and Nonmetal Mines.

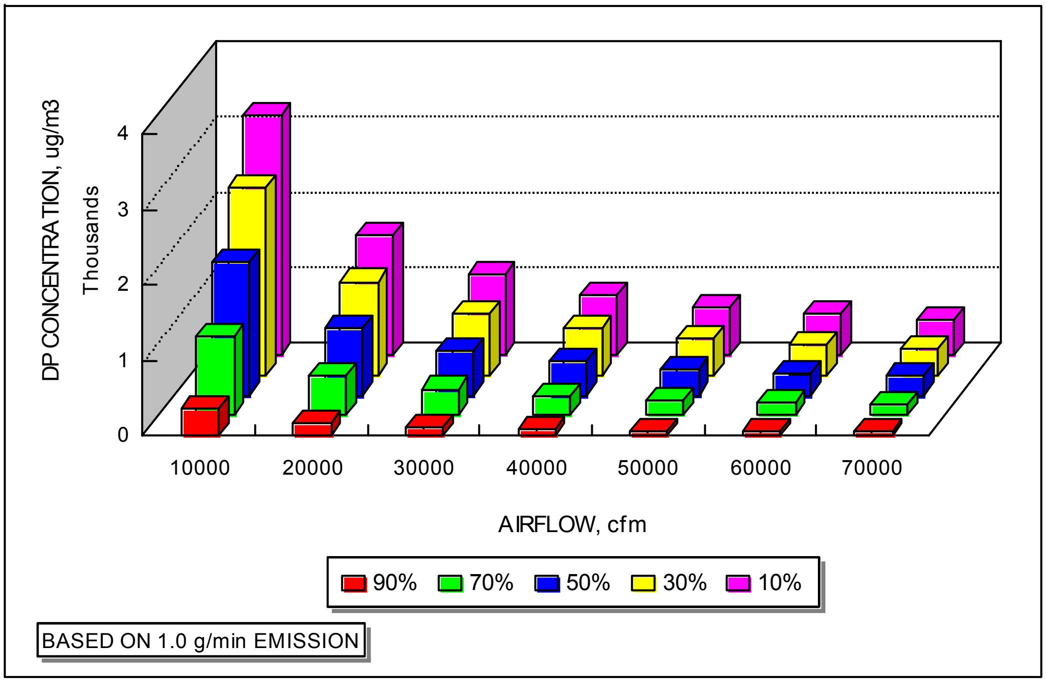

Figure 5. Interrelationship of Diesel Particulate Levels to Emission Rate, Ventilation Rate and Control Efficiency.